Final Technical Report

Submitted to the
U.S. GEOLOGICAL SURVEY

By the Seismological Laboratory
CALIFORNIA INSTITUTE OF TECHNOLOGY

Grant No.:	Award No. G16AP00147
Name of Contractor:	California Institute of Technology
Principal Investigator:	Dr. Egill Hauksson Caltech Seismological Laboratory, MC 252-21 Pasadena, CA 91125 hauksson@gps.caltech.edu
Government Technical Officer:	Jill Franks External Research Support Manager Earthquake Hazards Program, USGS
Title of Work:	Analysis of Earthquake Data From the Greater Los Angeles Basin and Adjacent Offshore Area, Southern California
Program Objective:	I & III
Effective Date of Contract:	1 July 2016
Expiration Date:	30 June 2017
Period Covered by report:	1 July 2016 – 30 June 2017
Date:	15 September 2017

This work is sponsored by the U.S. Geological Survey under Contract Award No. G16AP00147. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessary representing the official policies, either expressed or implied of the U.S. Government.

Analysis of Earthquake Data from the Greater Los Angeles Basin and Adjacent Offshore Area, Southern California

U.S. Geological Survey Award No. G16AP00147

Key words: Geophysics, seismology, seismotectonics

Egill Hauksson

Seismological Laboratory, California Institute of Technology,
Pasadena, CA 91125
Tel.: 626-395-6954
Email: hauksson@gps.caltech.edu
FAX: 626-564-0715

ABSTRACT

We synthesize and interpret local earthquake data recorded by the Caltech/USGS Southern California Seismographic Network (SCSN/CISN) in southern California. The goal is to use the existing regional seismic network data to: (1) refine the regional tectonic framework; (2) investigate the nature and configuration of active surficial and concealed faults; (3) determine spatial and temporal characteristics of regional seismicity; (4) determine the 3D seismic properties of the crust; and (5) delineate potential seismic source zones. Because of the large volume of data and tectonic and geologic complexity of the area, this project is a multi-year effort and has been divided into several tasks.

RESULTS

Evolution of seismicity near the southernmost terminus of the San Andreas Fault: Implications of recent earthquake clusters for earthquake risk in southern California

Three earthquake clusters that occurred in the direct vicinity of the southern terminus of the San Andreas Fault (SAF) in 2001, 2009, and 2016 raised significant concern regarding possible triggering of a major earthquake on the southern SAF, which has not ruptured in more than 320 years. These clusters of small and moderate earthquakes with $M \leq 4.8$ added to an increase in seismicity rate in the Brawley seismic zone that began after the 1979 Mw6.5 Imperial Valley earthquake, in contrast to the quiet from 1932 to 1979. The clusters so far triggered neither small nor large events on the SAF. The mostly negative Coulomb stress changes they imparted on the SAF may have reduced the likelihood that the events would initiate rupture on the SAF, although large magnitude earthquake triggering is poorly understood. The relatively rapid spatial and temporal migration rates within the clusters imply aseismic creep as a possible driver rather than fluid migration.

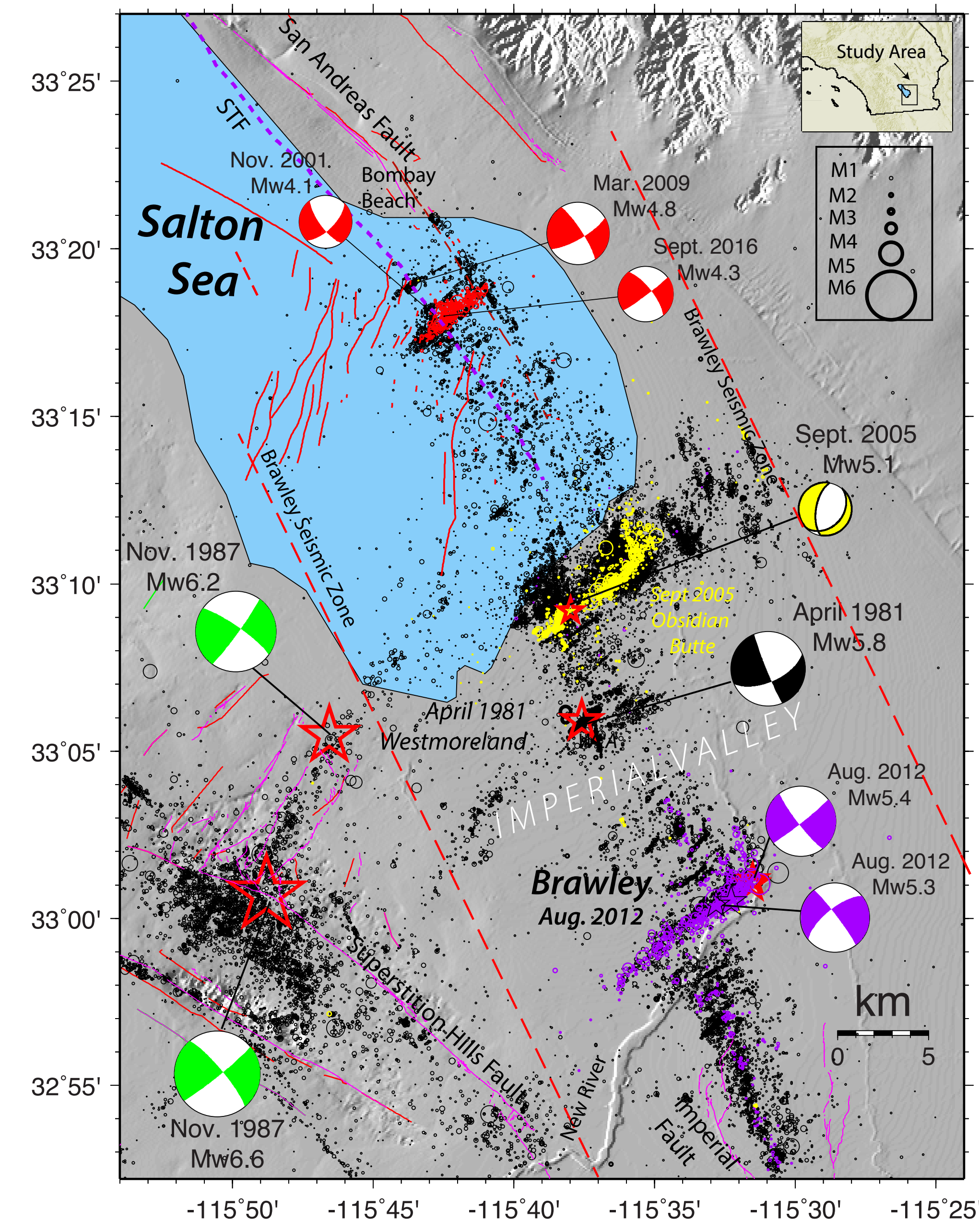

Figure 1. *Map of 1981-2016 relocated seismicity of the BSZ shown as black circles. The lower-hemisphere focal mechanisms for larger events that are labeled include: 1981 Westmoreland; 1987 Elmore Ranch and Superstition Hills (green); Obsidian Butte 2005 (yellow); Brawley 2012 (purple); and the Bombay Beach 2001, 2009, and 2016 (red). Elmore Ranch and Superstition Hills moment tensors are from Bent et al. [1989], and Yang et al. [2012]. The late Quaternary faults are from Jennings and Bryant [2010]; normal faults beneath the Salton Sea and the offshore extension of the SAF are from Brothers et al. [2009]. The Salton Trough fault (STF) is from Sahakian et al. [2016].*

The BSZ is the ~60 km long transtensional step-over between the SAF in the north and the Imperial fault (IF) in the south [*Johnson and Hill,* 1982]. Recently *Brothers et al.* [2009] mapped a zone of hinge faults with oblique slip close to the trace of the SAF (2ure 1) using active seismic reflection techniques. These faults lie within the northernmost extent of the BSZ transitioning to the SAF, and consist of numerous short, en echelon fault segments, and mostly exhibit normal motion with the down drop block to the southeast.

Three times in the last 15 years in 2001, 2009, and 2016, clusters of small earthquakes occurred within a few kilometers distance of the southern terminus of the SAF, near the eastern part of the hinge zone faults (Figure 1). These clusters with largest magnitudes of $4.0 \leq M \leq 4.8$ were located in the depth range from 3 to 10 km about 1 to 5 km southwest of the inferred trace of the SAF but within the northern BSZ. All three clusters had strike and dip different from the hinge faults, confirming the presence of unmapped strike-slip faults. The three clusters are spatially offset from each other and appear to be on different structures.

The temporal and spatial evolution of the three clusters differs significantly. The 2001 cluster lasted only for 24 hours, and formed an almost linear distribution extending from southwest to northeast. The 2009 cluster consisted of two sub-clusters lasting for 30 days, each with a northeast trend, but spaced ~5 km apart. The three day long 2016 cluster was located in between the 2001 and 2009 clusters extending for ~6 km. The rapid spatial expansion of each cluster with migration rates of up to ~2 km/hr could have been caused by aseismic slip over a larger fault area, but no geodetic data are available to confirm this inference.

A steady rate of background seismicity is not observed near the onshore SAF but does mark the off-shore trace of the SAF since at least 1981, or the start of the high precision catalog (Figure 1). These ~390 events have magnitudes ranging from ~1.0 to 3.5, and are located within 1.5 km distance using a 3D velocity model, mostly to the east of the inferred trace of the SAF, and thus the SAF may dip steeply to the east-northeast. This steady rate of seismicity suggests that the abutting BSZ is affecting the long-term state of stress along the offshore terminus of the SAF. However, the SAF remained locked during the three clusters because none of the three clusters seem to cause detectable aftershocks near the SAF *(for more detail, see Hauksson et al., 2017)*.

Abundant off-fault seismicity and orthogonal structures in the San Jacinto fault zone

The trifurcation area of the San Jacinto fault zone has produced more than 10% of all earthquakes in southern California since 2000, including the June 2016 Mw (moment magnitude) 5.2 Borrego Springs earthquake. The fault splits into three sub-parallel strands and is associated with broad VP/VS anomalies. We synthesize spatio-temporal properties of historical background seismicity and aftershocks of the June 2016 event. A template matching technique is used to detect and locate more than 23,000 aftershocks, which illuminate highly complex active fault structures in conjunction with a high-resolution regional catalog. The hypocenters form dipping seismicity lineations both along strike and nearly orthogonal to the main fault and are composed of interlaced strike-slip and normal faults. The primary faults change dip with depth and become listric by transitioning to a dip of ~70° near a depth of 10 km. The Mw 5.2 Borrego Springs earthquake and past events with M> 4.0 occurred on the main faults, where as most of the low-magnitude events are located in a damage zone (several kilometers wide) at seismogenic depths. The lack of significant low-magnitude seismicity on the main fault traces suggests that they do not creep. The very high rate of aftershocks likely reflects the large geometrical fault complexity and perhaps the relatively high stress due to a significant length of time elapsed since the last major event. The results provide important insights into the physics of faulting near the brittle-ductile transition.

Figure 2 shows the locations of 9,891 aftershocks alongside the relocated seismicity from 1981 to the present. A few aftershocks occurred on the CL fault itself, and most events were generated in a broad region between the CL and BR faults. The newly detected aftershocks are highly clustered in space and delineate numerous structures that are not resolvable from the network catalog alone. Closer examination reveals lineations with a range of length scales oriented nearly orthogonal to the main structures (inset). Several of the largest seismicity clusters trending in a northeast direction appear to have been activated for the first time in at least 35 years. They are composed of events with diverse focal mechanisms, including right-lateral strike-slip, normal, and, to a lesser extent, reverse faulting. This behavior is notable because in May 2008, a pair of M4.1 and M4.2 events occurred in almost the same location as the 2016 main shock but did not trigger similar seismicity that was detected by the regional network. Of the nine aftershocks in the 2016 sequence with M> 3.0, more than half are normal faulting. Such diversity in focal mechanisms is observed across the entire aftershock data set as well as in a previous focal mechanism catalog for the same area. (For additional details, see *Ross et al., 2017*).

To better understand the relationship between the seismicity and the three main faults, we examined the hypocenters as a function of depth. In a fault-normal cross section (A–A′), containing all events within 5 km of the profile. Numerous structures are delineated in the seismicity, including several that dip toward the northeast. Dashed lines indicate the most likely positions of the fault planes for CC, CL, and BR at these depths. These positions were determined by the locations of the 2008 Mw 4.1, 2010 Mw 5.4, 2013 Mw 4.7, and 2016 Mw 5.2 events together with their focal mechanisms and nearby lineations of seismicity. Additional significant lineations are visible and are likely minor fault strands. The CL, CC, and BR faults appear to dip ~70° to the northeast below a depth of about 10 km. The measured dip angles are in agreement with the focal mechanisms of several events with M> 4.0. If these dip angles are correct, the faults must be listric and transition to a near-vertical orientation at a depth of approximately 10 to 13 km; otherwise, they would intersect the surface several kilometers to the southwest of the surface traces, which is unlikely. An additional line of evidence for this transitionary behavior is that the lineations and focal mechanisms in the upper 6 to 10 km are markedly more vertical than those in between depths of 10 and 16 km. The aftershocks of the 2016 Borrego Springs earthquake primarily occupy the region between the CL and BR faults (red dots). Similar to the historical seismicity, they also demonstrate faint but persistent lineation dipping at ~70°.

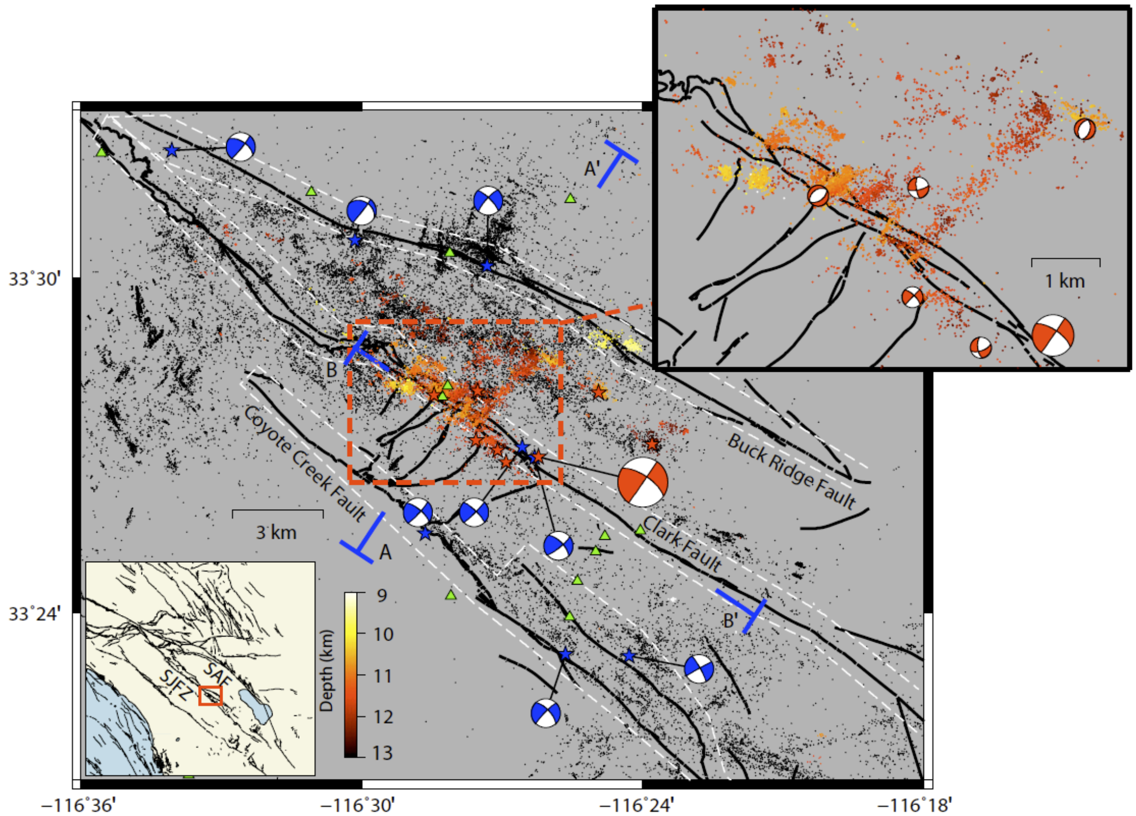

Figure 2*. Map of the trifurcation area of the SJFZ. Historical seismicity is denoted by black dots (20). Events with M> 4.0 that have occurred in this area since 2001 are indicated by blue stars and focal mechanisms. Aftershocks of the 2016 Borrego Springs earthquake are colored by depth. Red stars and focal mechanisms indicate aftershocks with M> 3.0. Stations used are denoted by green triangles. The inset contains a close-up of the detected aftershocks, which delineate numerous strike-slip and normal faults in conjugate orientations. SAF, San Andreas fault.*

References

Hauksson, E., Z. E., Ross, M.-A. Meier, and L. M. Jones (2017), Evolution of seismicity near the southernmost terminus of the San Andreas Fault: Implications of recent earthquake clusters for earthquake risk in southern California, *Geophys. Res. Lett.,* 44, doi:10.1002/2016GL072026

Ross, Z. E., E. Hauksson, Y. Ben-Zion (2017), Abundant off-fault seismicity and orthogonal structures in the San Jacinto fault zone., *Science Advanced,* 3, doi: e1601946

Recent refereed publications

Hauksson, E., Z. E., Ross, M.-A. Meier, and L. M. Jones (2017), Evolution of seismicity near the southernmost terminus of the San Andreas Fault: Implications of recent earthquake clusters for earthquake risk in southern California, *Geophys. Res. Lett.,* 44, doi:10.1002/2016GL072026

Ross, Z. E., E. Hauksson, Y. Ben-Zion (2017), Abundant off-fault seismicity and orthogonal structures in the San Jacinto fault zone., *Science Advanced,* 3, doi: e1601946

Castro, R. R., J. Stock, E. Hauksson, and R. Clayton (2017), Active tectonics in the Gulf of California and seismicity (M>3.0) for the period 2002-2014, *Tectonophysics*, http://dx.doi.org/10.1016/j.tecto.2017.02.015

Castro, R. R., J. Stock, R. Clayton, and E. Hauksson (2017), Observations of remotely triggered seismicity in Salton Sea and Coso geothermal regions, southern California, after big (Mw>7.8) teleseismic earthquakes, *Geofisica Internacional, in press, Jan.*

Ross, Z. E., H. Kanamori, and E. Hauksson (2017), Anomalously large complete stress drop during the 2016 Mw 5.2 Borrego Springs earthquake inferred by waveform modeling and near-source aftershock deficit, *Geophys. Res. Lett.,* 44, doi:10.1002/2017GL073338.

Ross, Z. E., E. Hauksson, Y. Ben-Zion , E. Cochran, C. Rollins, and J.-P. Avouac, (2017) Aftershocks driven by afterslip and fluid pressure sweeping through a fault-fracture mesh; *Accepted, Geophys. Res. Lett*, Aug. 2017

Yu, C., Z. Zhan, E. Hauksson, E. Cochran, (2017) Strong *SH*-to-Love Wave Scattering off the Southern California Continental Borderland, *Submitted to Geophys. Res. Lett*, Aug. 2017

Goebel, T. H. W., S. M. Hosseini, F. Cappa, E. Hauksson, J.-P. Ampuero, F. Aminzadeh and J.B. Saleeby (2016), "Wastewater disposal and earthquake swarm activity at the southern end of the Central Valley, California", *Geophys. Res. Letts*, 43, 1-8, doi:10.1002/2015GL066948.

Kohler, M. D., A. Massari, T. Heaton, H. Kanamori, E. Hauksson, R. Guy, R. Clayton, J. Bunn, and K. M. Chandy (2016), Downtown Los Angeles 52-story High-Rise and Free-Field Response to an Oil Refinery Explosion*, Earthquake Spectra*, Volume 32, No. 3, pages 1793–1820,doi: http://dx.doi.org/10.1193/062315EQS101M;

Hauksson, E., J. Andrews, A. Plesch, J. H. Shaw, and D. R. Shelly (2016), The 2015 Earthquake Swarm Near Fillmore, California: Possible Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin, *Seismological, Res. Letters,*87 ,4 ,p807-815 , doi: 10.1785/0220160020

Abstracts for recent oral, reports, or poster presentations

Ross, Z. E., Hauksson, E., Maechling, P. J., Beroza, G. C., (2017), Using GPU clusters to detect millions of small earthquakes in southern California with template matching; (Abstract) presented at the *2016 Seismological Soc. America meeting in Denver, CO, 18 April 2017*

Hauksson, E., Meier, M. A., Ross, Z. E., Caltech, Jones, L. M. (2017), Triggering of major earthquakes near the southernmost terminus of the San Andreas fault: implications of recent earthquake clusters for earthquake risk in southern California; (Abstract) presented at the *2016 Seismological Soc. America meeting in Denver, CO, 19 April 2017*

Hauksson, E., Regional tectonic stress field and earthquake stress drops in southern California: Understanding distributed continental plate boundary tectonics; (Abstract) presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Alvarez, M., Thomas, V., De Cristofaro, J., US Geological Survey, Pasadena, Ca, USA; Hauksson, E., Bhadha, R., Stubailo, I., Bruton, C. P., Watkins, M. B. (2017) The Southern California Seismic Network, a multi-purpose seismic observatory; (Abstract) presented at the *2016 Seismological Soc. America meeting in Denver, CO, 19 April 2017*

Goebel, T. H., W., Hosseini, S. M., Cappa, F., Hauksson, E., Ampuero, J. P., Aminzadeh, F., Saleeby, J. B., Wastewater Disposal and Earthquake Swarm Activity at the Southern End of the Central Valley, California. (Abstract) to be presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Goebel, T. H. W., Hauksson, E., Plesch, A., Shaw, J. H., Seismicity Statistics and Stress in Regions with High Tectonic Complexity: A Comparative Study of the Greater San Gorgonio and Ventura Regions in Southern California. (Abstract) presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Castro, R. R., J. Stock, E. Hauksson, R. Clayton, Source Functions and Path Effects from Earthquakes in the Farallon Transform Fault Region, Gulf of California, Mexico that occurred on October 2013; (Abstract) presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Castro, R. R., R. Clayton, E. Hauksson, and J. Stock, Observations of Remotely Triggered Seismicity in Salton Sea and Coso Regions, Southern California, After Big (M_W>7.8) Recent Earthquakes; *(Abstract), to be Presented at 2016 IASPEI Costa Rica*.

Castro, R., R. Clayton, E. Hauksson, J. Stock, Disparo Remoto de Sismicidad en las Regiones de los Campos Geotermicos del Salton Sea y Coso, Sur de California, Despues de Telesismos Grandes (Mw>7.8); (Abstract), Union Geofisica Mexicana (UGM) meeting, fall 2016.

Cochran, E. S., Kohler, M. D., Given, D. D., Andrews, J., Meier, M.-A., Hauksson, E., Minson, S., Ahmad, M., DeLeon, J., Guiwits, S., ShakeAlert Testing and Certification Platform: Point Source and Ground Motion Based Evaluations, 2016 Incorporated Research Institutions for Seismology Workshop, Vancouver, WA, 2016.

Plesch, A., Nicholson, C., Sorlien, C. C., Shaw, J. H., & Hauksson, E. (2016). CFM Version 5.1: New and revised 3D fault representations and an improved database. (Abstract; Poster) SCEC Annual Meeting Palm Springs, 11 Sept. 2016.

Ross, Z. E., E. Hauksson, and Y. Ben-Zion , Complex active faults and seismicity rates in the trifurcation area of the San Jacinto fault zone illuminated by aftershocks of the 2016 Mw 5.2 Borrego Springs earthquake, (Abstract; Poster) SCEC Annual Meeting Palm Springs, 11 Sept. 2016.

Hauksson, E., Z. E. Ross, and C. Yu, Heterogeneous State of Stress and Seismicity Distribution Along the San Andreas Fault in Southern California: New Insights into Rupture Terminations of Past Earthquakes; Abstract **T43E-3102:** presented at 2016 Fall Meeting, AGU, San Francisco, Calif., 15 Dec.